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THE SUSTAINING NEUTRAL BEAM POWER SUPPLY SYSTEM FOR THE MIRROR FUSION TEST FACILITY

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DISCLAIMER

THE SUSTAINING NEUTRAL BEAM POWER SUPPLY SYSTEM*
FOR THE MIRROR FUSION TEST FACILITY

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Summary

A fixed-price procurement contract for $24.9 million was awarded to Aydin Energy Division, Palo Alto, CA, for the design, manufacture, installation, and acceptance testing of the sustaining neutral beam power supply system (SNBPSS). This system is scheduled for completion in early 1981 and will provide the conditioned power for the 24 neutral beam source modules. Each of the 24 power supply sets will provide the accel potential of 80 kV at 88 A, the arc power, the filament power, and the suppressor power for its associated neutral beam source module.

Recent workshops at LLL and LBL resulted in changes to the neutral beam source module requirements that reduce the complexity of SNBPSS and make the sources easier to operate and less susceptible to fault-induced damage. The accel voltage rise time was reduced from a maximum of 100μ s to 200μ s; the k factor proportional to perveance was changed to a variable rather than being a constant of 4 in the $I_{arc} = k\ V_{acc}\ ^{1.5}$ relationship; and multiple changes were made to the arc source input, one of which was the added requirement for an "arc spot" detector and a fast crowbar circuit for source protection.

A computer model of the SNBPSS was made by SRI, a consultant to Aydin Energy Division, and by LLL for the system design and performance confirmation. The Stanford Research Institute (SRI) computer model results led Aydin to make a significant design change from an RC compensation network at the output of the accel dc power supply to a shunt switch tube arrangement that is coordinated with the series modulator tube.

System Design

In late August 1978 we awarded a fixed-price procurement contract for $24.9 million for the design, fabrication, installation, and acceptance testing of the SNBPSS. This system, which is scheduled for completion in early 1981, will provide the power conditioning requirements for the twenty-four 80-kV, 80-A, sustaining neutral beam injectors to be installed on the Magnetic Fusion Test Facility (MFTF).

Each power supply furnishes a neutral beam injector with 80-kV, 88-A, acceleration pulses of up to 30-s duration repeated at 5-min intervals. In addition, each set provides the filament, arc, and suppressor grid power requirements for its associated injector.

System Installation

The 24 accelerator dc power supplies for the system will be installed outdoors on a concrete pad next to the substation supplied from the dedicated 230-kV power line. The supplies will be clustered in four groups of six, with each group enclosed within a single security fence. The pulse power modulators will be installed on the mezzanine floors in the MFTF building, with each group of six also enclosed within a single security fence. The pulse power modulators will consist of the accelerator modulators and the associated filament, arc, and suppressor grid power supplies for the injector. A control console will be located outside the security fence in Bldg. 431. Any two of a group of six power supplies can be operated simultaneously from this console for acceptance testing or maintenance. For normal operations, the SNBPSS will be controlled from a central supervisory computer.

SNBPSS Component Changes

Recent workshops and discussions at LLL and LBL concerning requirements of the MFTF 80-kV neutral beam injector sources and the SNBPSS have resulted in a number of component changes that will reduce the complexity of SNBPSS and make the sources easier to operate and less susceptible to fault induced damage.

Figure 1 shows a block diagram of the major SNBPSS components on the left and a schematic diagram of the ion source on the right. The SNBPSS components are the accel dc power supply, accel modulator, filament power supply, arc power supply, gradient grid network, suppressor power supply, and control and monitor system. The major parts of the injector source are the filament, arc anode, entrance grid, suppressor grid, and exit grid.

The first change was to relax the accel voltage risetime requirement to the sustaining neutral beam injector source from 20-100μs to 20-200μs. This slow risetime will simplify the accel modulator design. The second change is to make k, a parameter that is proportional to source perveance, into a variable (instead of a constant value of 4) in the relationship of $I_{arc} = kV_{acc}\ ^{1.5}$. This change will make the injector more tunable and easier to operate.

Arc Power Supply Requirements

The arc power supply requirements were reexamined with two principal goals in mind:

- Incorporation of new requirements for injector protection and control.
- Relaxation of existing requirements where possible to simplify the arc power supply circuit designed by Aydin (Fig. 2). These changes will provide MFTF with a more reliable sustaining neutral beam system with a minor cost impact.

New experimental data on neutral beam injectors required the following additions to the arc power supply:

- Addition of a crowbar to the output of each power supply to protect the arc chamber from localized heating during spotting.

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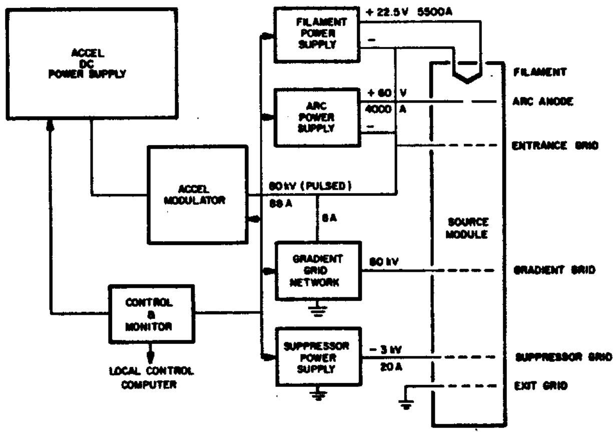


Fig. 1: Block Diagram of SNBPSS

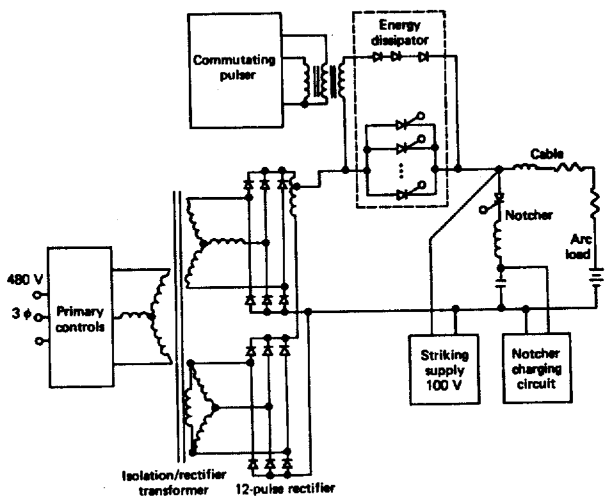


Fig. 2: SNBPSS Arc Power Supply Design Proposed By Aydin

• Expansion of the control circuitry to permit open-loop tracking of the accel voltage to the rise of the arc current with a variable waveshape and with up to ± 100-μs time offset (Fig. 3). This provides the needed flexibility for optional injector operation.

Major simplification of the arc power supply resulted from the following experimental results:

• A well-conditioned neutral beam injector will spark-down no more than two or three times during a 0.5-s pulse.

• A risetime anywhere from 20 to 200 μs is sufficient for reliable injector operation.

The reduction in the number of spark-downs enables a substantial cost savings in the arc power supply. The minimum time between notches can be relaxed from the original requirement of 2.5 ms to 25 ms. This enables the energy dissipator and commutating pulser hardware, shown in Fig. 2, to be eliminated. This hardware was required to prevent a gradual buildup in arc current whenever several notches occurred in succession spaced only 2.5 ms apart. The new requirement of 25 ms between notches eliminates this hardware and therefore increases the reliability of the power supply.

The slower risetime of the accel voltage previously mentioned results in a slower risetime of the arc current and permits a major simplification of the cable between the power supply and the neutral beam source. With the notcher circuit tuned for a 100-μs risetime, the cable inductance can be raised from 0.35 to 6 μH without greatly affecting the notcher--charging circuit. The cable can be changed from 126 individual conductors to only six. The higher cable inductance also makes the notching characteristic less dependent on both the type of gas being used in the injector and the individual injector characteristics.

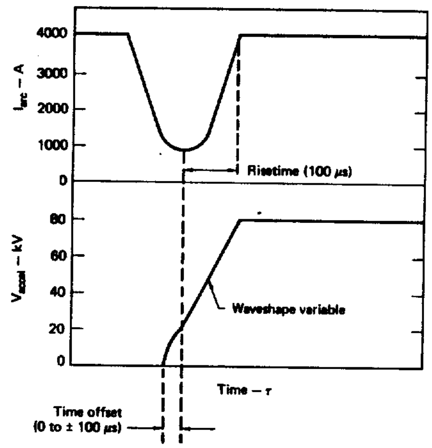


Fig. 3: Relationship between arc current And Accel Voltage

Several other changes made in the arc power supply requirements have a minor impact:

• The minimum open circuit voltage was reduced from 100 to 30 V to reflect new data on arc striking voltage.

• The minimum arc current was raised from 300 to 600 A.

o The notching depth was changed from below 300 A to 240 A or 20% of the prenotch arc current, whichever is greater.

• The requirement of 40 μs below 570 A during the notch interval was eliminated.

• The arc current maximum ripple requirement of 4% from 300 to 4000 A was changed to a more limited current range from 1500 to 4000 A with the power supply operating into an injector arc load.

Changing the minimum open-circuit voltage requirement permitted elimination of an auxiliary supply in parallel with the main arc supply (see Fig. 2). The other changes affect component size but do not permit component elimination.

A frequent source of potentially destructive faults is the formation of localized internal arcs in the arc chamber. These faults usually occur between the arc plasma and the filaments and are fed by the arc power supply. This process is called spotting and the localized arcs are called spots. We will add a detector to sense the occurrence of spotting. A fast arc current crowbar will also be added to protect the injector from spotting by shunting the arc current rapidly away from the injector arc anode.

Computer Modeling Verification of SNBPSS

The SNBPSS design is being verified by computer modeling of the total system using the EMTP and SCEPTRE code at LLL and the ASTAP code at SRI. The LLL study is more of a global analysis, with emphasis on protecting the neutral beam sources and preventing harmful interactions between power supply subsystems; SRI is concentrating more on the Aydin power supply design. ASTAP was used by Aydin and SRI to analyze the Princeton TFTR modulator regulator.

EMTP Code

The EMTP code is being used to model the 230/13.8-kV pulse-power substation and 12 accel dc power supplies. We are investigating the effect on system performance resulting from failure of major components; for example, an internal arc in the modulator tube. Should this arc occur, the crowbar in that power supply is automatically switched on. This causes the dc output voltage in the 11 adjacent power supplies to drop nearly 7 kV in the 25 ms required to interrupt power to the disabled power supply. One of two steps must then be taken: Either we turn off the 11 power supplies, or we reduce accel current to the neutral-beam source modules. Experience at Los Alamos Scientific Laboratory (LASL) using similar modulator tubes indicates that crowbars due to modulator tube arcs should not occur more often than once every 200 h of tube operation.

SCEPTRE Code

The SCEPTRE code is used to model the pulse-power modulator and the neutral beam source cable. Accel current waveforms as a function of modulator turn-off times, cable capacitance, and snubber designs are being studied.

ASTAP Code

ASTAP is a very powerful analytical tool that can model very complex circuits, such as the one shown in Fig. 4. One section of the extended delta rectifier transformer for the accel dc power supply (Fig. 5) and the rectifier assemble (Fig. 6) were modeled to evaluate the effects of switching the high-voltage output of the dc power supply into a 1000-ohm resistive load. The data (Fig. 7) show the effect of the switching transient on the power supply voltage.

Aydin was faced with two design constraints. One was the power rating of the primary ac equipment such as the tap switch voltage regulator, the rectifier transformer, and the rectifiers. To control equipment costs and minimize the power dissipated in the output series resistor, it was necessary to hold the dc output voltage to a value as low as possible. The other constraint was to maintain an adequate voltage drop across the series tube of at least 6 kV to allow for continuous regulation. The 6 kV is required so that even with 2 kV of ripple on the dc voltage and 1 kV of short term ac voltage change, there will always be at least 1 kV anode-to-screen voltage and 2 kV screen-to-cathode voltage.

Figure 7 shows the data from an SRI computer run showing the input voltage to the series regulator tube with a 61 μf capacitor bank in the compensation network. Notice that the undershoot at turn on reduces the voltage level to 86 kV, the minimum value permitted to maintain regulation with 80 kV being supplied to the load. For the remainder of the pulse, the anode voltage is 90 kV; the anode to cathode voltage is 10 kV. This means that the average tube dissipation during the on time is near the maximum rated tube dissipation of 1 MW.

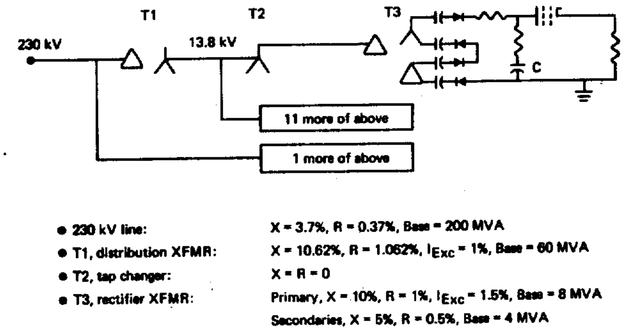


Fig. 4: SNBPSS One Line Diagram

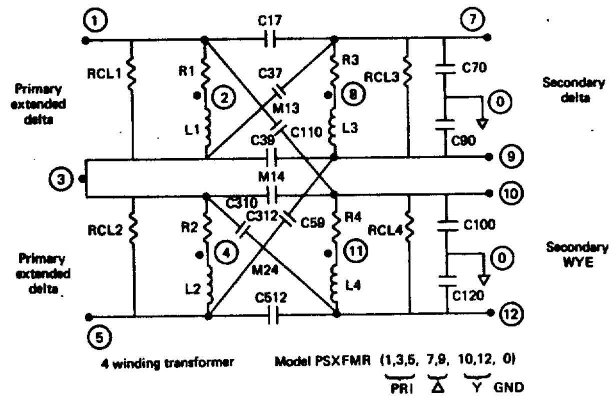


Fig. 5: Extended Delta Rectifier TransformerASTAP Computer Model

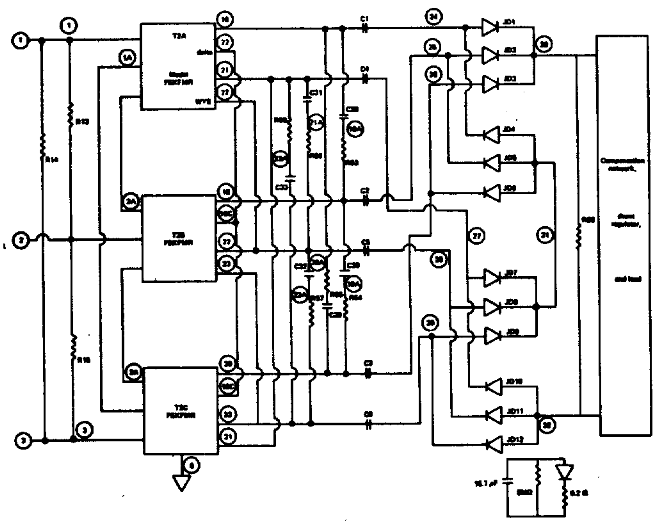
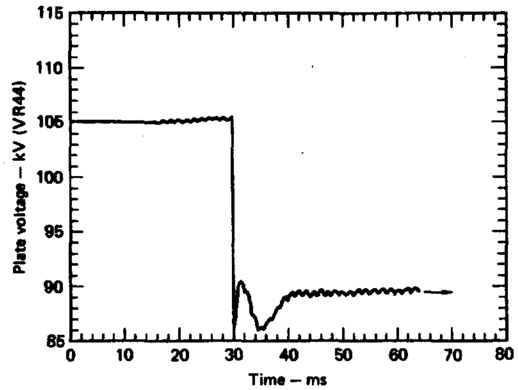


Fig. 6: Rectifier Assembly ASTAP Computer Model



Notes:
1G, 12P, passive, 61.4 µF, 227.9 Ω, 63.5 Ω + 100 Ω, 8 MVA
PPSM2G – 5140

Fig. 7: The Accel dc P.S.
Output Transient Voltage

The size and cost of the 61-µf, 120-kV capacitor bank was excessive, so Aydin developed an alternate design. They used a second CQK 200-4 tetrode as a shunt conditioning switch. It will be turned on slowly (50 to 100 ms) so that the transient effects on the primary power line are minimal. Once the predicted output current is achieved, the shunt tetrode will be switched off and the series tube switched on simultaneously. Ideally, this operation will have no effect on the primary line since the current it is delivering will not change. To compensate for slight timing variations during the switching operation, a 5-µf capacitor is placed across the shunt tube. When the pulse is terminated, the series tube is turned off and the shunt tube is turned full on, and then slowly ramped down to zero. Figure 8 shows the simplified one-line diagram of the present pulse power modulator using the shunt conditioning switch.

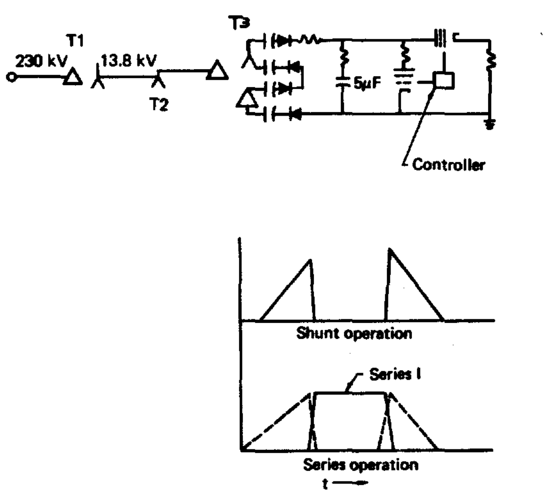


Fig. 8: Pulse Power Modulator
Using The Shunt Conditioning Switch

Arc Power Supply Transformer Design

The analysis by SRI was also instrumental in developing information in the design of the arc power supply transformer. It was determined that all published information on calculating transformer reactance had significant errors when dealing with 12 pulse rectifier systems where the transformer reactance was purposely maintained at very large values (50% and higher). The mutual inductances between every winding and every other winding have to be determined and fed into the model in order to obtain accurate results. Since Aydin had not experienced this requirement before, prototype transformers had to be built and measurements taken.

Conclusions

A single contract was awarded to design, fabricate, install and perform the acceptance tests of the total SNBPSS system. With a single contractor having full system responsibility it has been possible to have close liaison and frequent workshops that have resulted in design optimization.

Computer modeling has been an important tool in developing the SNBPSS design with the ASTAP code being used by the contractor and the EMTP code being used by LLL. The performance of the arc power supply, the filament power supply and the pulse power modulator were improved by the use of the computer models.

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